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Enhanced transmission beyond the cut-off through sub-λ Annular Aperture Arrays

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Abstract

A cascaded structure of annular aperture arrays perforated in silver films is shown to act as a high quality Fabry-Pérot interferometer (quality factor up to 200). The transmission of a single nanostructured layer exhibits a cut-off wavelength beyond which there is no transmission. It is demonstrated, here, that the double structure permits to overcome this cut-off. It is also found that transmission is enhanced by a factor of 150 for certain wavelengths. This kind of cascaded nanostructured metallic layers offers many promising applications as well as for optical wavelengths than for THz-waves because this effect still exists for perfect metals. It opens up the path for the conception of a new generation of integrated components based on metallo-dielectric structures that can be easily tailored as tunable devices.

Enhanced transmission through subwavelength apertures engraved in metallic films is now a wide area of research. Transmission through Annular Apertures Arrays (AAA) is a sub-domain of these researches. 90 % transmission in the visible range can be achieved with sub-λ coaxial apertures arranged into a square lattice [1, 2]. This large transmission is due to one identified guided mode (TE_{11}-like mode) propagating inside each cavity [3]. The structure is a low-pass filter for wavelengths smaller than a cut-off ($\lambda_c^{TE_{11}}$). A typical transmission spectrum is presented in figure 1. The guided mode, excited by the diffraction of the linearly polarized incident beam, can propagate inside the cavity with very weak losses in spite of the real nature of the used metal. A lot of studies were devoted to the fabrication and the characterization of AAA structures made in silver, gold or other metals [4–8].

What is important to note in figure 1 is that the position of the main transmission peak (i.e. the cut-off wavelength of the infinite coaxial waveguide) depends both on the geometrical parameters of the annular aperture and on the used metal. It does not depend on the metal thickness. Thus, if we want to increase the value of the cut-off, we should expand the outer radius (or simultaneously the inner one) of the aperture which is obviously limited by the distance between two apertures i.e. by the period of the structure. This last value has to be chosen in order to cancel any surface plasmon resonance near the cut-off [9] and then the period must be smaller than the cut-off wavelength (for normal incidence).

To bypass this restraint, we firstly propose to use a cascaded structure composed of two identical perforated metallic layers (cf. figure 2). This idea has already been applied in the infrared range for holes [10] or slits [11] arrays in metallic films. In our case, each of these layers consists of a square lattice of annular apertures of period $p = 300nm$, inner radius $R_i = 75nm$ and outer radius $R_o = 100nm$ made in a $h = 100nm$ thick silver film.

In the following, the distance between the two layers is named d and ε is the dielectric constant of the intermediate medium.

To simplify the discussion, we first consider a "self-suspended" structure where the intermediate medium is vacuum ($\varepsilon = 1$). Second, we suppose that there is no lateral shift between the two structures, the apertures are then one in front of the other ($L_x = L_y = 0$ in figure 2). These two assumptions, that are not restrictive at all, are taken in order to have a simple explanation of the theoretical results.

The numerical study is done with a home-made Finite Difference Time Domain (FDTD) code. It includes a non uniform meshing in order to fulfill an accurate description of the fine details of the structure. The parameters of the calculations are given in the figures caption. Note that throughout this study, the illumination parameters are kept the same as in figure 1.

The spectral response (zero order transmission) of a single layer is depicted in figure 1. The maximum of transmission is located near the cut-off wavelength $\lambda_c^{TE_{11}} = 926.5nm$ and reaches 88%. The corresponding peak is relatively wide and shows a small but a non zero transmission for wavelengths greater than the cut-off. This property is of big importance. In fact, this small transmission, which corresponds to a very large reflection, can be increased, as classically, by the use of a Fabry-Pérot (FP) interferometer.

As mentioned above, the FP interferometer is designed by cascading two metallic layers as presented in figure 2. Figure 3 shows the transmission spectrum of the double structure where the distance between the two metallic layers is fixed to $d = 600nm$. Two peaks, which are FP harmonics, appear in the transmission spectrum in addition to the wide one previously observed with the single structure. These peaks do not only appear for wavelengths smaller than the cut-off but also for those larger than $\lambda_c^{TE_{11}}$.

It is interesting to note that around the cut-off, the transmission is due to the guided mode inside the apertures and should appear whatever the FP thickness is. Then, its value is equal to the square of the transmission of a single layer. All these explanations are valid in the case where there are no FP harmonics near the cut-off.

To confirm these statements, we computed the transmission spectra for a range of values of d varying from $100nm$ to $600nm$ (see figure 4). As described above, the two FP peaks are visible and their positions depend on the FP thickness whereas the wide peak always occurs at the cut-off. When d varies, the positions of the two peaks change according to the law of phase matching $2\sqrt{\varepsilon}e = m\lambda$ where e is the *effective* thickness of the FP and $m \in \mathbb{Z}$. As it will be discussed further, the value of e depends both on the nature of the metal and on the geometrical parameters of the apertures.

When a FP peak approaches the cut-off, there is a coupling between the two phenomena namely the guided mode and the FP resonance as demonstrated in figure 4. Far from the cut-off, the peak positions vary almost linearly with d.

In order to gain a more physical insight, an analytical approach for the calculation of the transmission through the double structure is given. As for a conventional FP, the transmitted energy can be written as:

$$T^{FP}(\lambda) = \frac{T(\lambda)^2}{[1 - R(\lambda)]^2 + 4R(\lambda)\sin^2(\frac{\phi}{2})} \tag{1}$$

where $T(\lambda)$ and $R(\lambda)$ are the energy transmission and reflection coefficients of the single metallic nanostructured layer of which the FP is composed. ϕ is the phase associated with the distance between the two layers. At normal incidence, its value is given by :

$$\phi = \frac{4\pi\sqrt{\varepsilon}e(\lambda)}{\lambda} \tag{2}$$

As it is well known, a small transmission $T(\lambda)$ of a single layer (i.e. large reflection coefficient $R(\lambda)$) leads, in the case of two layers, to a large value of the quality factor $Q(\lambda)$. The variations, versus the wavelength, of these three quantities are shown in figure 5 where $Q(\lambda)$ is determined as for a conventional Fabry-Pérot by $Q(\lambda) = \frac{\pi\sqrt{R(\lambda)}}{1-R(\lambda)}$. In addition, the absorption ($A(\lambda) = 1 - R(\lambda) - T(\lambda)$) is also reported and it is found to be negligible except around the cut-off. Consequently, a FP based on two of such layers will lead to high transmission at its resonances.

From figure 5, it is clear that at the cut-off wavelength the quality factor has a very small value because no FP resonance occurs; the light directly channels through the two metallic layers as a guided wave inside the annular apertures ($R = 0$).

Usually, the phase ϕ is determined from the geometrical distance d between the two metallic layers. This is valid when the penetration depth e_m of light in the metal is very small compared to d. However, for small values of d, e_m must be taken into account. $e_m(\lambda)$ can be easily determined by : $e_m(\lambda) = \frac{\lambda}{2\pi n"(\lambda)}$ where $n"(\lambda)$ is the imaginary part of the index given also by $n" = Im(\sqrt{\varepsilon_m(\lambda)})$, ε_m being the dielectric permittivity of the metal. Figure 6 shows that even if the phase in equation 1 is corrected by replacing e with $d + e_m(\lambda)$, the obtained spectra are still slightly different from those of figure 4.

Consequently, the effective thickness of the FP can be written as the sum of *three* terms:

$$e(\lambda) = d + e_m(\lambda) + e_g(\lambda) \tag{3}$$

where $e_g(\lambda)$ is the geometrical penetration depth induced by the nanostructuration of the single metallic layer. By combining the results of figures 4, 6 and the value of $e_m(\lambda)$ obtained by using the Drude model [1], $e_g(\lambda)$ can be deduced as it is shown in figure 7.

Note that e_g becomes negative for $\lambda \in [733nm, \lambda_c^{TE_{11}}]$. In fact the effective index of the guided mode can be smaller than 1 [12] that leads, obviously, to $e_g < 0$. Accordingly, the structure can be seen as a metamaterial more precisely a left-handed material. Note that $e_g(\lambda)$ is not defined for all the wavelengths corresponding to guided modes.

For the right part of the curve ($\lambda > \lambda_c^{TE_{11}}$), there is no guided mode but the light passes through the metallic structure by tunneling. In this case, the metallic layer acts as an homogeneous layer with effective permittivity and thickness. Consequently, the transmission decays exponentially with the wavelength.

It is of fundamental importance to note that the previous behaviour is not sensitive to the lateral shifts L_x and L_y (see figure 2) between the two layers. Computations, not reported here, fortunately show that varying L_x and L_y from 0 to $p/2$ does not affect at all the transmission spectrum. Then, the alignment of the AAA layers is not a technological constraint for the fabrication of such a device. This property is only valid if the two layers are far enough so that no near-field coupling occurs.

To demonstrate the potentiality of this structure, we extend the study to other electromagnetic domains by considering the case of AAAs made in perfect conductors. This corresponds to metals in the far infrared, terahertz or microwave domains. Figure 8 shows the transmission spectrum through the same structure when silver is replaced by a perfect conductor and when dimensions are in microns instead of nanometers.

Because the used metal is lossless, the transmission can reach 100%. If we cascade two structures, the transmission behaviour shows additional peaks corresponding to the harmonics of the equivalent FP interferometer.

As in the case of a real metal, peaks can appear far beyond the cut-off wavelength of the guided mode. The position of the wide peak (located at $\lambda_c^{TE_{11}}$) is independent of the distance between the two metallic layers. Whereas the positions of the FP peaks depend on the distance d. It is also obvious that for perfect conductor $e_m(\lambda)$ is equal to zero. Therefore, the discrepancy between d and e, that occurs also in the case of perfect conductor metals, is only due to the additional geometrical penetration depth $e_g(\lambda)$ that can be also determined from equation 3. For example, figure 8 leads to $e_g = 60\mu m$ at $\lambda = 1260\mu m$.

In summary, a complete study of the transmission through cascaded AAAs has been presented and the mechanisms involved in the electromagnetic interactions have been elucidated. The results based on a numerical method (FDTD method) show a good agreement with an analytical model. Many applications can be founded upon this promising structure both in the optical and THz domains. For the visible range, this cascaded AAA structure can be used to design submicrometric interferometers with very high Q factor or to build nanometric-sized modulators by replacing vacuum between the two metallic layers with an electro-optical material such as lithium niobate. In the THz range, this device can also be used to enhance the emission of quantum-cascade lasers [13, 14]. Other applications for Radom-Radar, spectroscopic detection or flat screens can also be designed from this interesting structure.

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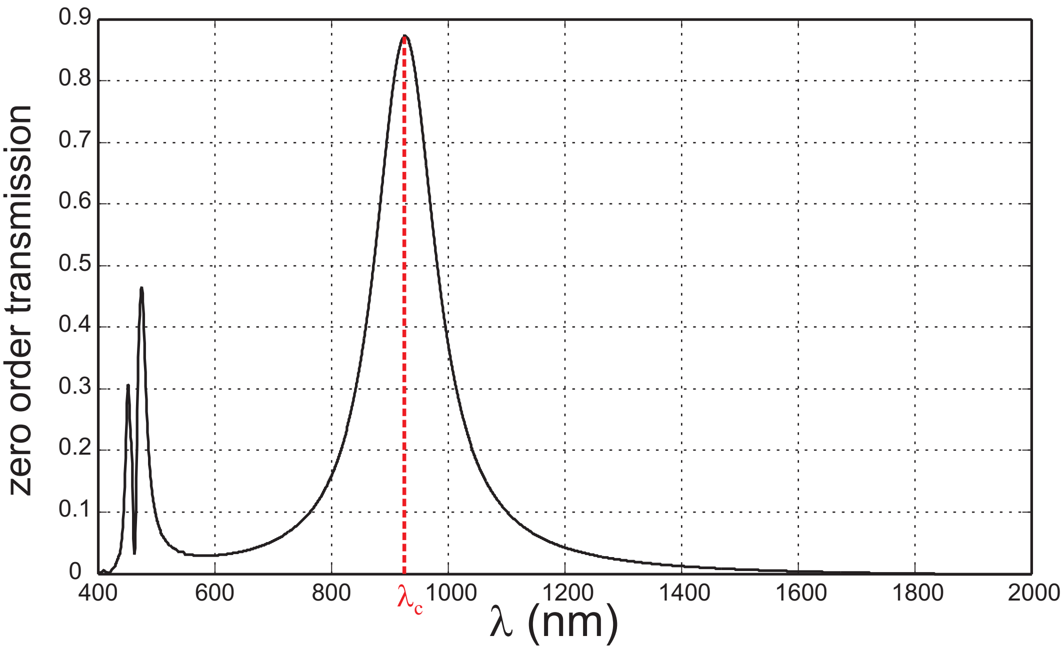

FIG. 1: Transmission spectrum through a single silver layer perforated with annular apertures arranged into a square array. The period is $p = 350nm$, the inner and the outer radii of the coaxial cavities are $R_i = 75nm$ and $R_o = 100nm$ respectively. The metal thickness is set to $h = 100nm$ and the structure is illuminated by a linearly polarized plane wave at normal incidence. The spatial step of the FDTD algorithm was fixed to $5nm$ for the metal structure and $25nm$ elsewhere. The metal dispersion ($\varepsilon_m(\omega)$) was also taken into account by a Drude model as in reference [1]. Note that because of the spatial discretization all geometrical parameters are defined with $5nm$ uncertainty.

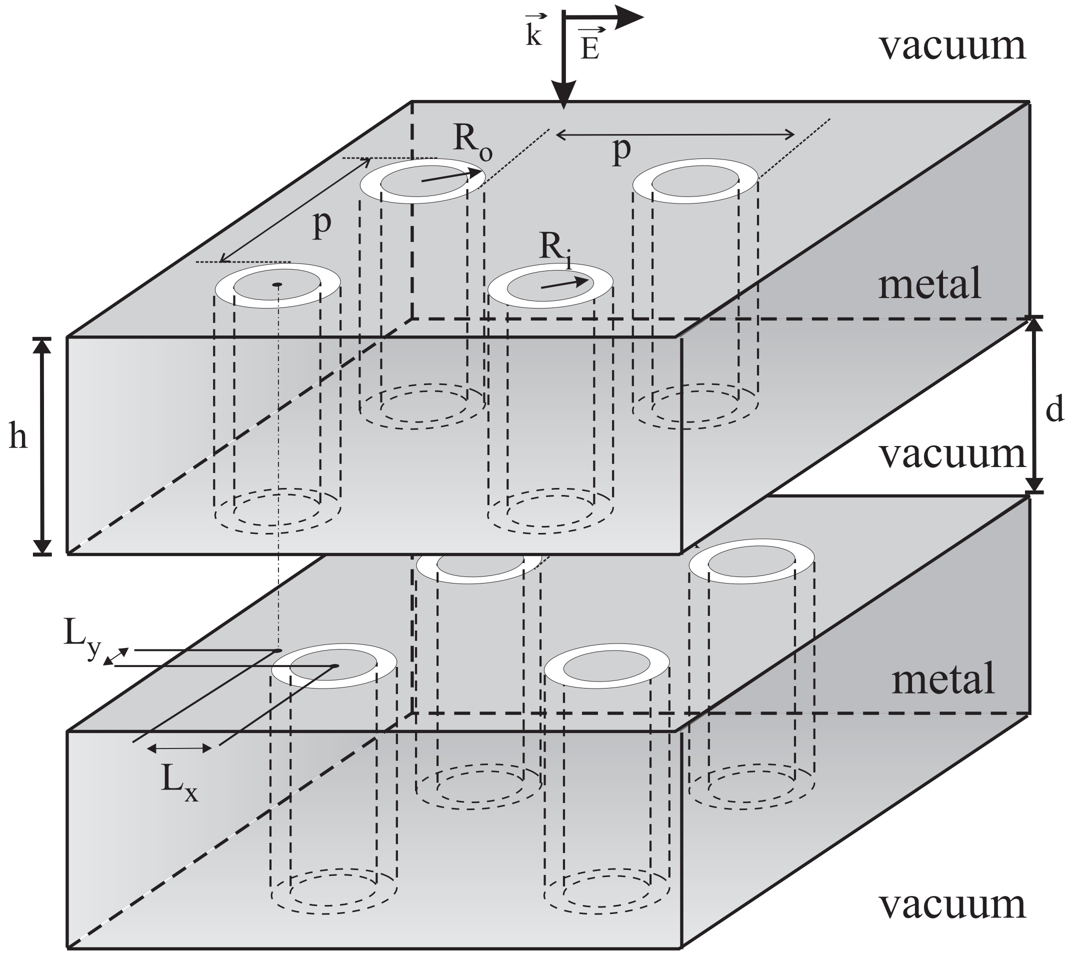

FIG. 2: Schematic view of the studied structure. As mentioned in figure 1, the period is noted p, the inner and the outer radius of the coaxial cavity are R_i and R_o respectively. The metal thickness is h, the distance between the two metallic layers is d and the structure is illuminated by a linearly polarized plane wave at normal incidence. L_x and L_y are lateral shifts along the x and y directions respectively.

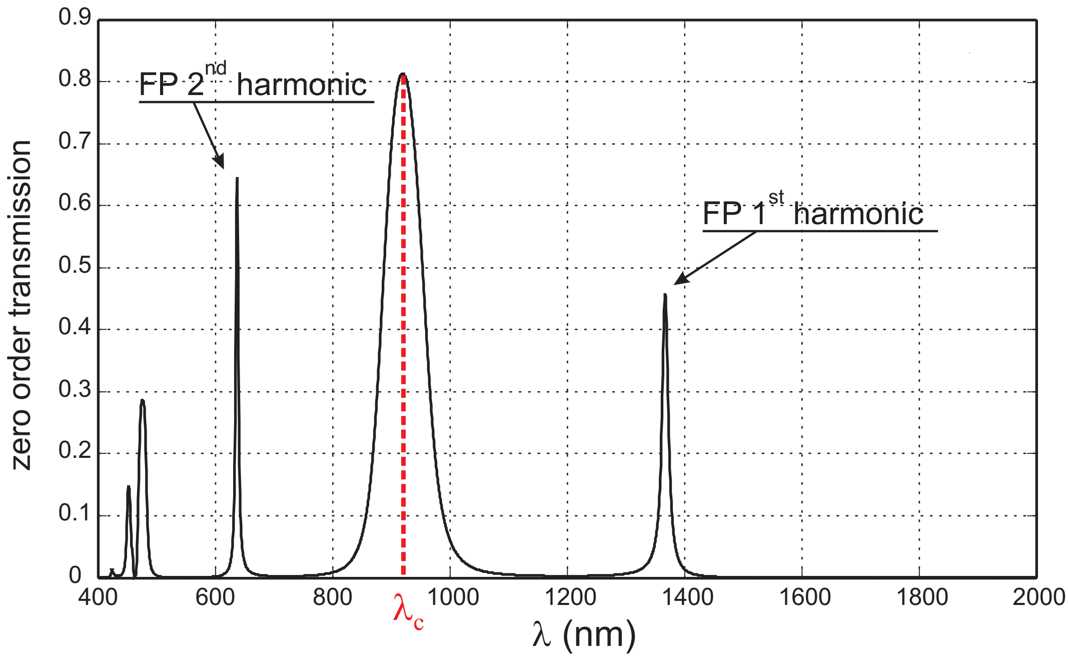

FIG. 3: Transmission spectrum of the structure presented on figure 2 for $p = 350nm$, $R_i = 75nm$, $R_o = 100nm$, $h = 100nm$ and $d = 600nm$.

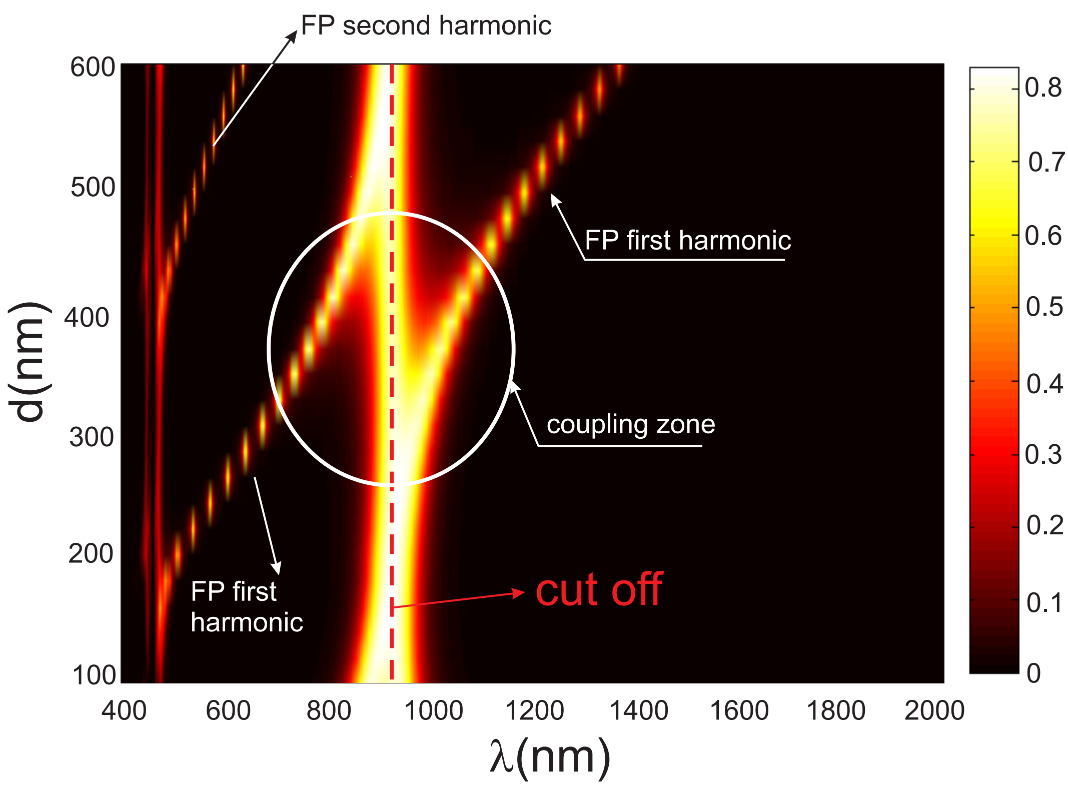

FIG. 4: Transmission in color level versus the wavelength and the distance between the two metallic nanostructured layers.

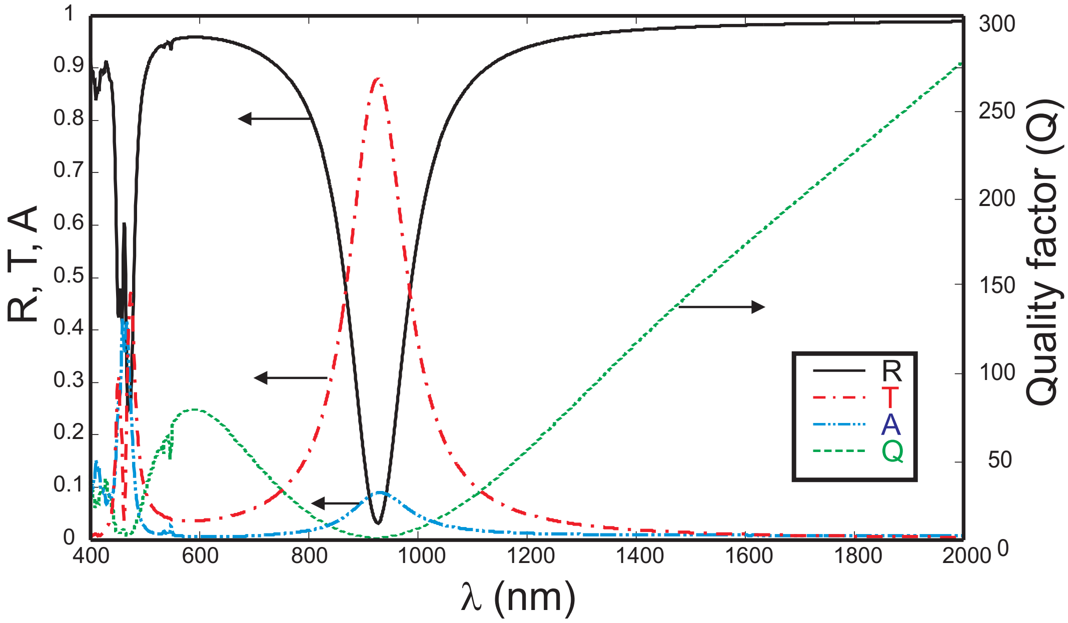

FIG. 5: Transmission (red dotted dashed line), reflection (black solid line) and absorption (blue dotted-dotted dashed line) spectra through a single metallic layer perforated with annular apertures arranged into a square array. The period is $p = 350nm$, the inner and the outer radius of the coaxial cavity are $R_i = 75nm$ and $R_o = 100nm$ respectively. The metal thickness is set to $h = 100nm$ and the structure is illuminated by an x-linearly polarized plane wave at normal incidence. The quality factor of the cascaded structure (dotted green line) is deduced from the reflection coefficient.

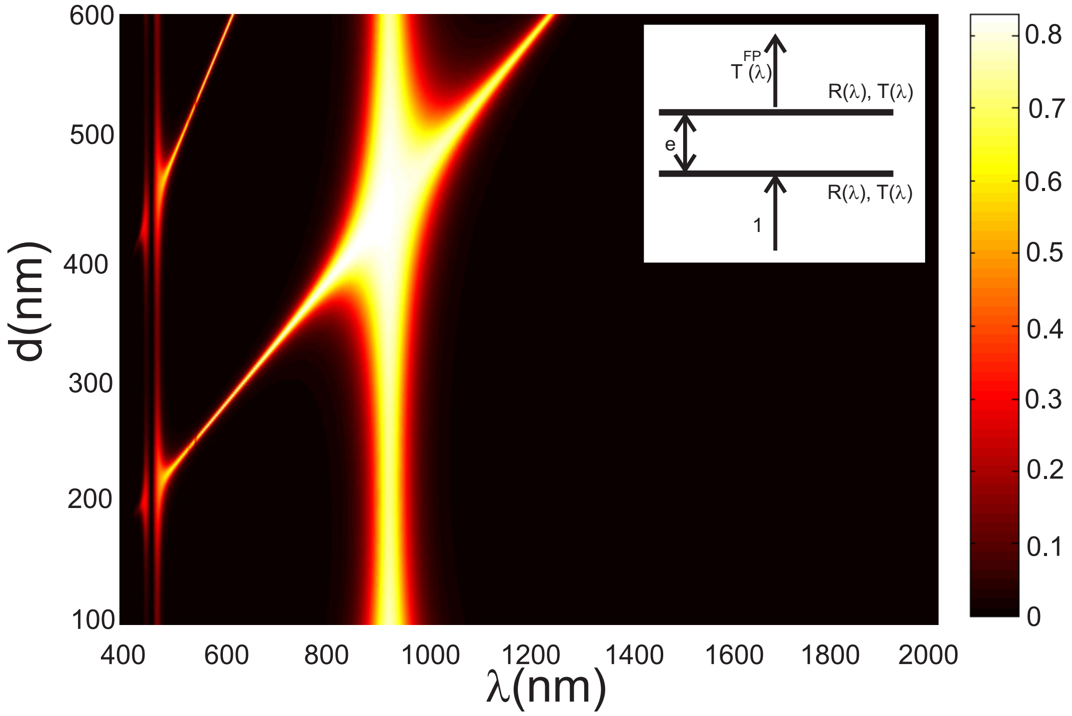

FIG. 6: Calculated transmission from equation 1 in color level versus the wavelength and for d varying form $100nm$ to $600nm$. The effective distance $e(\lambda)$ between the two metallic structures is replaced by $e = d + e_m(\lambda)$ in equation 1. The inset shows the theoretical schema used to calculate the transmission of the double structure.

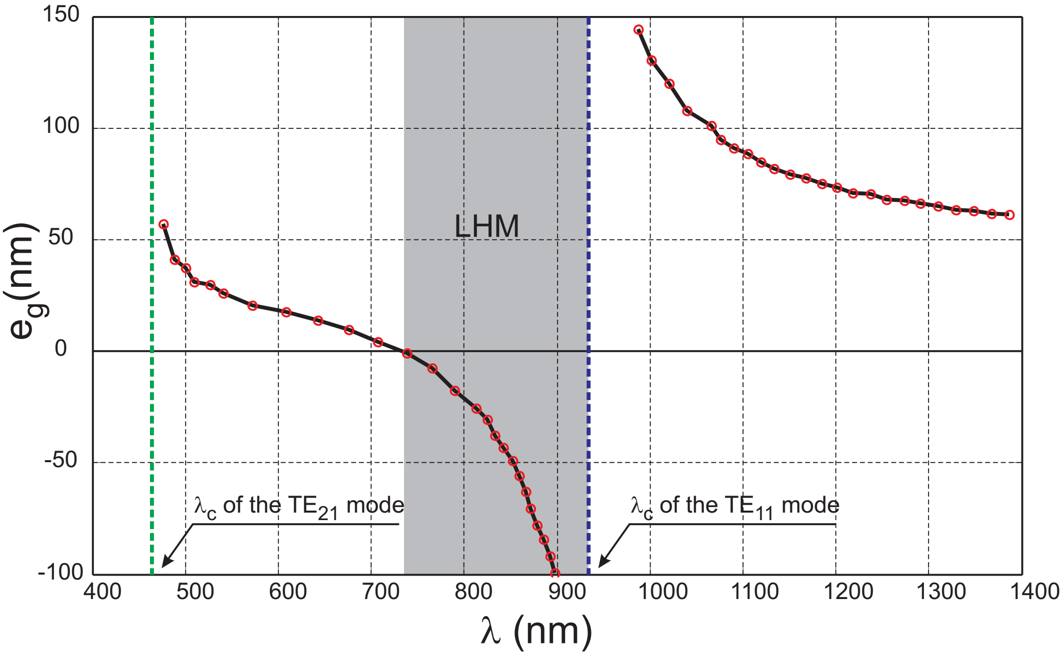

FIG. 7: Geometrical penetration depth of the electromagetic wave (defined by equation 3) versus the wavelength. The shaded zone corresponds to $e_g < 0$ which means that the matallic layers behave as a Left-Handed Material (LHM).

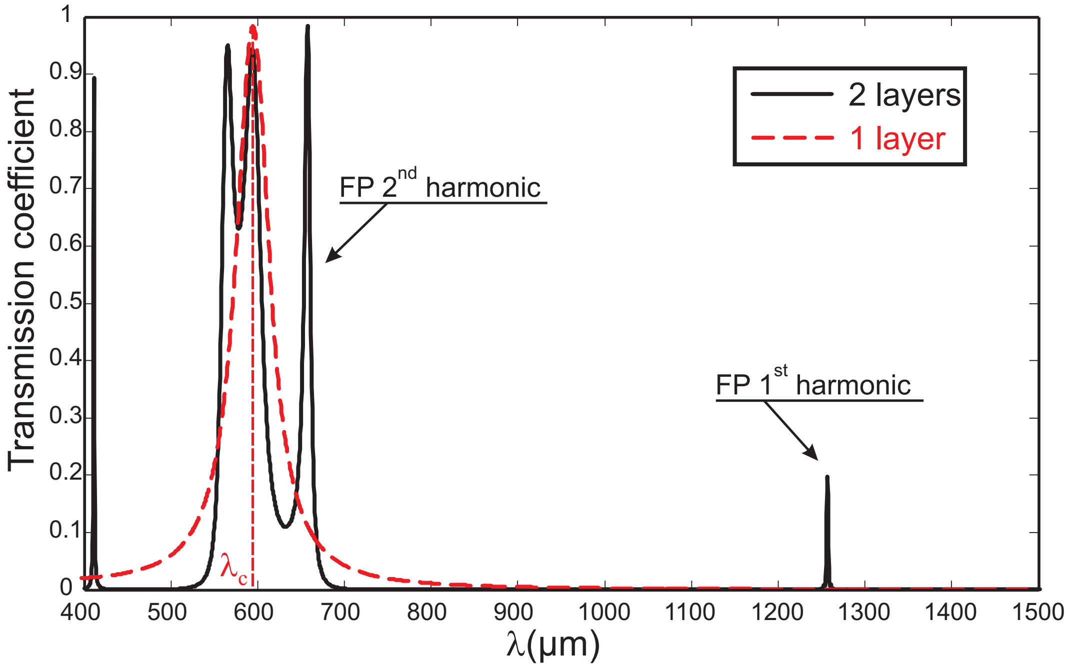

FIG. 8: Transmission spectra of a single structure (dashed ref line) and of two cascaded metallic layers (solid black line) in the case of a perfectly conducting metal. For the two calculations, the period is $p = 350\mu m$, the inner and the outer radius of the coaxial cavity are $R_i = 75\mu m$ and $R_o = 100\mu m$ respectively. The metal thickness is set to $h = 100\mu m$ and the structure is illuminated by a linearly polarized plane wave at normal incidence. For the cascaded structure, the distance d was fixed to $d = 600\mu m$. Note that the transmission at the wavelength of the first FP harmonic is enhanced by a factor 150.